Numerical simulations of reverberation chamber

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Master Thesis in Telecommunication Engineering
Abstract

The focus of this project is to determine whether commercial general purpose ray-based electromagnetic analysis tool (XGYD by Remcom, Inc.) can be an effective and accurate method of simulating a reverberation chamber and wireless communication within a confined and reflective environment, like a car.

An introduction that includes the mathematical equations which govern the wireless channel is given in this memory, as well as a summary of the models, methods and strategies that we have implemented to preview the effects that the environment produces.

In order to accomplish the goal of the project, it was first necessary to learn the management of the ray tool software, namely Remcom XGTD. With XGTD we were able to define the geometry of the environment and simplify it. On the other hand, other software like AutoCAD and Excel is also used. As mentioned before the main objective of this project is to evaluate if it is possible to use ray tool software in order to obtain real values. Different scenarios are studied; a reverberation chamber with an X-paddle, a reverberation chamber with a complex stirrer, a real engine compartment and two versions of a car, one accurate CAD model and a simplified model. The car chose was an Opel Meriva, since we have his empirical wideband wireless channel model.

We found that the XGTD results are suitable to know the early-time field build up after the source is switched on, but cannot predict the steady-state fields of high reflective enclosures because of the intractably large number of ray reflections required for convergence.
Acknowledgements

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I would like to thank the professor Olivier Delangre, who has been my tutor in this project and without his patience, knowledge and disinterested help this project would have not been possible; and to thank the professor Philippe De Doncker for offering me the opportunity to work in this project. I would like to thank the ‘Service de Ondes et Signaux’ of the ‘Université Libre de Bruxelles’ (ULB) for the technical support and the given facilities for elaborating this project.

Finally, to the person who changed my life.
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<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>( \theta )</td>
<td>Propagation angle</td>
<td>rad or degrees</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Dielectric constant</td>
<td>F·m(^{-1})</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Permeability constant</td>
<td>H·m(^{-1})</td>
</tr>
<tr>
<td>( f )</td>
<td>Frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Wavelength</td>
<td>m</td>
</tr>
<tr>
<td>( Z )</td>
<td>Wave impedance</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Conductivity</td>
<td>S/m</td>
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<tr>
<td>Rx</td>
<td>Reflection coefficient</td>
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<tr>
<td>T</td>
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<td>rad or degrees</td>
</tr>
<tr>
<td>L</td>
<td>Losses</td>
<td>dB</td>
</tr>
<tr>
<td>P</td>
<td>Received or transmitted Power</td>
<td>dBm or W</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Time constant</td>
<td>s</td>
</tr>
<tr>
<td>( \tau_{RMS} )</td>
<td>Delay Spread</td>
<td>S</td>
</tr>
<tr>
<td>Bc</td>
<td>Coherence bandwidth</td>
<td>Hz</td>
</tr>
<tr>
<td>( \rho_0(\varphi) )</td>
<td>Correlation coefficient</td>
<td></td>
</tr>
<tr>
<td>( \varphi )</td>
<td>Angular distance</td>
<td>degrees</td>
</tr>
<tr>
<td>( \sigma_i^2 )</td>
<td>Variance</td>
<td></td>
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<tr>
<td>Q</td>
<td>Quality factor</td>
<td></td>
</tr>
<tr>
<td>( U_T )</td>
<td>Total stored energy</td>
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</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>m(^3)</td>
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<tr>
<td>SR</td>
<td>Stirring Ratio</td>
<td>dB</td>
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<tr>
<td>( R^2 )</td>
<td>Determination parameter</td>
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<table>
<thead>
<tr>
<th>Constants</th>
<th>Description</th>
<th>Values</th>
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<tbody>
<tr>
<td>( \varepsilon_0 )</td>
<td>Free space dielectric constant</td>
<td>8.854E-12 F·m(^{-1})</td>
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<tr>
<td>( \mu_0 )</td>
<td>Free space</td>
<td>4( \pi )E-12 H·m(^{-1})</td>
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<tr>
<td>( c )</td>
<td>Free space phase velocity</td>
<td>3E08 m/s</td>
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II. PREFACE

II.1 Origin

In February of 2007 the professor Philippe De Doncker of the department of ‘Ondes et Signaux’ of the ULB University in Brussels offered me the opportunity in working in the field of computer simulation. The professor Olivier Delangre guided and helped me during the thesis. The project consists in simulating a reverberation chamber by commercial software of ray tracing called Remcom XGTD. This software can give us a model to compare with real results.

II.2 Motivation

Since the last few years, the unprecedented growth of communication systems involving the propagation of electromagnetic waves is particularly due to developments in mobile phone technology.

The communications inside vehicles become very interesting to the car industry for enhanced passenger connectivity; applications could be in the area of multimedia devices as video terminals or navigation. But it could be also possible to monitor some parameters as temperature, the level of oil or petrol, or the air pressure. Wired network systems are unattractive due to significant additional space, weight, and maintenance costs. Wireless networks are an obvious choice due to much lower space, weight and maintenance requirements.

For various reasons, use of wireless phones is currently prohibited while the aircraft is in the air. Recent flight demonstrations show that wireless phone use on airplanes is technically possible. In these demonstrations, wireless phones communicated with the on-board picocell base-stations rather than directly with the ground towers.

Finally, the wireless system can replace all the electric system, even safety critical sensors and actors that affect the safe function of the vehicle (like the brake or the steering system), as the electric system replaced many mechanical parts in the past.
The exact knowledge of the channel characteristics is important to assess different modulations schemes in regard of their suitability for the data transmission in vehicles. This environment is particular since many reflections are present with few or no specular ones.

The reverberation chamber is a reliable bench-test, enabling the study of the effects of electromagnetic waves on a specific electronic appliance. It has for many years been used to test antennas and electromagnetic interferences, this thesis is very original compared to existing literature since the reverberations chamber will be used to characterize some parameters of this channel as it is a high reflective environment too.

II.3 Outline

This project is introduced by a general review about propagation mechanism in order to have an overview of the wireless channel interactions.

This project is organized so that the reader could understand without knowing in depth about wireless propagation or reverberation chambers, from where it starts, how it advances and where it goes.

This project is introduced by a general review about propagation mechanism in order to have an overview of the wireless channel interactions, once introduced the basic phenomena, the most important channel parameters and models are presented. As the reverberation chamber may be not known by the most public the theoretical background and basic foundation of RCs is introduced next. To finish the bibliographic part a basic introduction to the Finite Difference Time Domain (FDTD) simulation method is included.

The second part, once the mathematical concept is understood, the models and the results are presented. Starting with the simpler model, the expectations, the problems, the solutions and the improvements are described until arriving to the simulation of a real environment.

In this thesis, we make the assumption, and will try to evaluate its validity, that a vehicle body can be analyzed using parameters similar to reverberation chamber.
From the electromagnetic point of view, the vehicle body is considered to be a loaded non-perfect cavity.

Finally, a final evaluation is done in conclusions.
PART I

BIBLIOGRAPHICAL REVISION
III. GENERAL REVIEW OF PROPAGATION MECHANISMS

III.1 Introduction

The plane waves are the natural solutions of Maxwell’s equations inside an environment lineal, homogeny and isotropic; regions where the constitutive parameters did not vary in space, being infinite in extend in all directions. In practice, we must consider the boundaries between media. The mechanisms which determine the wave’s propagation, the received power levels and the channel depend of the wavelength, the objects between the transmitter and the receiver, and the closes objects.

This section will describe the ways in which the interactions between plane waves and infinite plane surfaces can be calculated, provided that the constitutive parameters are known.

III.2 Reflection, Refraction and Transmission

The received signal depends of the sum of all the different ray contributions. These rays are identified as (1) simple line of sight (LOS) rays, (2) specular reflecting rays from surfaces, (3) diffracting rays around obstacles, and (4) transmitted rays through walls where refraction and absorption can occur. All such rays are shown schematically in Figure 3.1. Rays can, and do, arrive at a receiver after multiple reflections, diffractions and transmissions.

Figure 3.1 Propagation phenomena
III.2.1 Snell’s Law Of Reflections and Refractions

When the plane wave incident interacts with a plane boundary with an angle of $\theta_i$, the result is that two new waves are produced, each with the same frequency as the incident wave. As shown in FIGURE 3.2, the first wave propagates within medium I, it makes an angle $\theta_r$ to the normal, and it’s called reflected wave. The angle of the reflected ray is related to the incidence angle as follows the equation (3.1), Snell’s law of reflection:

$$\theta_i = \theta_r \quad (3.1)$$

The second travels on into medium II, making an angle $\theta_t$ to the surface normal. This is the transmitted wave, which results from the mechanism of refraction. The angle of transmission is also related to the incidence angle and is given by the equation (3.2) & (3.3), Snell’s law of refraction:

$$\frac{\sin \theta_i}{\sin \theta_t} = \sqrt{\frac{\varepsilon_2 \cdot \mu_2}{\varepsilon_1 \cdot \mu_1}} \quad (3.2)$$

$$\frac{\sin \theta_i}{\sin \theta_t} = \frac{n_2}{n_1} \quad (3.3)$$

Where $n$ is the refractive index, which is the ratio of the free space phase velocity, $c$, to the velocity in the medium $v$. 

Figure 3.2 Interactions with the boundary plane
Numerical simulations of reverberation chamber

\[ n = \frac{c}{v} = \sqrt{\frac{\mu \varepsilon}{\mu_0 \varepsilon_0}} \]  \hspace{1cm} (3.4a)

The **refractive index** can also be defined as:

\[ n = \sqrt{\varepsilon' - j \frac{\sigma}{\omega \varepsilon_0}} \]  \hspace{1cm} (3.4b)

Where \( \varepsilon' \) is the real part of the permittivity and \( \sigma \) is the effective conductivity of the material.

Snell’s laws follow from Freamt’s principle of least time.

In addition the interaction between the wave and the boundary plane also causes the energy to be split between the reflected and transmitted waves. The amplitudes of the reflected and transmitted waves are given relative to the incident wave amplitude by the **Fresnel reflection and transmission coefficients**. The coefficients are different for cases when the electric field is parallel and normal to the scattering plane, denoted by subscripts \( \parallel \) and \( \perp \) respectively. The coefficients are denoted by \( R \) for the reflection and \( T \) for the transmission. The particular equations for non magnetic environments:

\[ R_\parallel = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_1} \]  \hspace{1cm} (3.5a)

\[ R_\perp = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_1} \]  \hspace{1cm} (3.5b)

\[ T_\parallel = \frac{2n_1 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_1} \]  \hspace{1cm} (3.6a)

\[ T_\perp = \frac{2n_1 \cos \theta_1}{n_1 \cos \theta_1 + n_2 \cos \theta_1} \]  \hspace{1cm} (3.6b)

To obtain the electric field we only need to make the division according to the vectors parallel \( \hat{e}_\parallel \) and perpendicular \( \hat{e}_\perp \) to the scattering plane.

\[ E_i = E_{i\parallel} + E_{i\perp} = E_{i\parallel} \hat{e}_{i\parallel} + E_{i\perp} \hat{e}_{i\perp} \]  \hspace{1cm} (3.7)

\[ E_r = E_{r\parallel} + E_{r\perp} = E_{r\parallel} R \hat{e}_{r\parallel} + E_{r\perp} R \hat{e}_{r\perp} \]  \hspace{1cm} (3.8)

\[ E_t = E_{t\parallel} + E_{t\perp} = E_{t\parallel} T \hat{e}_{t\parallel} + E_{t\perp} T \hat{e}_{t\perp} \]  \hspace{1cm} (3.9)
Consequently, the resolution of a problem of incidence on dielectrics media is limited to the calculation, by means of the laws of Fresnel, of the values of the reflection and transmission coefficients of the boundary, according to the incidence angle. Once known these values, the equations (3.8) and (3.9) allow us to calculate the electric field independently of which their polarization state is.

Notice how the coefficients of reflection depend of the material, the polarization, the frequency and the incidence angle. The figure 3.3a and 3.3b shows the magnitude of the losses for dry ground and wet ground for a frequency of 5 GHz.

III.2.2 Special angle

A special case is that in which no reflection takes place in the surface of separation between both media. This can be noticed in figure 3.3; the reflection goes to zero at one angle. At this angle, the waves polarized lineally with the vector parallel to the incidence plane are not reflected. This angle is called the Brewser angle, $\theta_i = \theta_B$, and is given by
Another special situation is where no energy is transmitted through the plane boundary, $T=0$ and $R=1$, so all the energy is reflected. The angle of incidence above which the total internal reflection occurs is called critical angle. The critical angle $\theta_c$ is given by:

$$\theta_c = \sin^{-1} \frac{n_s}{n_i}$$

(3.11)

### III.2.3 Rough Surface Scattering

The reflection processes discussed so far have been applicable to smooth surfaces only; this is termed *specular reflection*. When the surface is made progressively rougher, the reflected wave becomes scattered from a large number of positions on the surface, broadening the scattered energy (Figure 3.4). This reduces the energy in the specular direction and increases the energy radiated in other directions. The degree of scattering depends on the angle of incidence and on the roughness of the surface in comparison to the wavelength. The apparent roughness of the surface is reduced as the incidence angle comes closer to grazing incidence ($\theta_i = 90^\circ$) and as the wavelength is made larger.

![Figure 3.4](image)

*Figure 3.4: The effect of surface roughness on reflection*

If a surface is to be considered smooth, then waves reflected from the surface must be only very slightly shifted in phase with respect to each other. If there is a height difference $\Delta h$ between two points on the surface, then waves reflected from those points will have a relative phase difference of...
\[ \Delta \phi = \frac{4\pi \Delta h \cos \theta_i}{\lambda} \]  

(3.12)

A reasonable criterion for considering a surface smooth is if this phase shift is less than 90°, which leads to the *Rayleigh criterion*:

\[ \Delta h < \frac{\lambda}{8\cos \theta_i} \]  

(3.13)

![Graph showing Rayleigh criterion for surface roughness for f=5GHz](image)

Figure 3.5: Rayleigh criterion for surface roughness for f=5GHz

The surfaces above the curve of Figure 3.5 cannot be accurately modeled using the Fresnel reflection coefficients alone. For these surfaces the reduction in the amplitude of the specular component may be accounted for by multiplying the corresponding value of \( R \) by a roughness factor \( f \), which depends on the angle of incidence and on the standard deviation of the surface height \( \sigma_s \). One formulation for this factor is:

\[ f(\sigma_s) = \exp \left[ -\frac{1}{2} \left( \frac{4\pi \sigma_s \cos \theta_i}{\lambda} \right)^2 \right] \]  

(3.14)
### III.3 Diffraction

Diffraction takes importance when considering fields in the *shadow region* behind an obstruction, as shown in figure 3.6. In this region the fields are not null due to the diffraction caused by the obstruction and it is possible the reception, although the attenuation is higher than the free space ones.

3.6 Huygen's principle for diffraction

This effect can most easily be understood by using *Huygen’s principle*:

1. Each element of a wavefront at a point in time may be regarded as the centre of a secondary disturbance, which gives rise to spherical wavelets.
2. The position of the wavefront at any later time is the envelope of all such wavelets.

Plane wavefronts who impinge on the edge become curved by the obstruction so that, deep inside the geometrical shadow region, rays appear to emerge from a point close to the edge, filling in the shadow region with diffracted rays.

The final result can be expressed as a *propagation loss*, which expresses the reduction in the field strength due to the diffraction process in decibels, it can be numerically evaluated using standard routines for calculating Fresnel integrals, or approximated for $v > 1$ with accuracy better than 1dB:

$$ L_{d_e}(v) = -20 \log \left( \frac{E_d}{E_i} \right) \approx -20 \log \frac{0.225}{v} \quad \text{(3.15)} $$
where $E_d$ is the diffracted field, $E_i$ is the incident field, and the parameter $\nu$ can be expressed in terms of the geometrical parameters defined in figure 3.7 as

$$\nu = h' \sqrt{\frac{2(d_1 + d_2')}{\lambda d_1'd_2'}} = \alpha \sqrt{\frac{2d_1'd_2'}{\lambda(d_1' + d_2')}}$$

(3.16)
IV. INTRODUCTION AT THE WIRELESS COMMUNICATION CHANNELS

IV.1 Introduction

The electromagnetic waves suffer several phenomena defined before, when two or more versions of the signal arrive at different times, they combine at the receiver resulting in a signal that can vary, not only, in amplitude and phase. While some paths will aid the direct path or make possible the communication in shadow regions, others can actually cause complete signal fading.

The application of previous equations would give us the exact value of every magnitude if we know the position, shape and composition of each object at the scenario. This is absolutely impossible as the scenario is not static. Therefore we must find an alternative way enough precise to estimate the reality and enough simple to be simulated by computer.

IV.2 Path Loss, Shadowing and Fast Fading

If we monitor the received power of a mobile terminal moving away of the transmitter antenna we can see a variation like the figure 4.1.

There are, at least, three components which affect the received power: the path loss (discontinuous line), de shadowing or slow fading (continuous line) and the fast fading (thin line).
The path loss is a function only of parameters such as antenna heights, environment and distance. It is fundamental for predicting the range of a mobile radio system determine the mean received power of a receiver vs distance. The accuracy of the path loss predictions is crucial in determining whether a particular system design will be viable. In macrocells, empirical models have been used with great success, free space, plane earth, Egli [EGLI-57], Okumura-Hata [OKUM-68][HATA-80], Lee [LEE-93], Walfish-Ikegami (urban), COST 231[WALF-88][IKEG-84][IKE-84][COST-231], etc. For indoor environments there are also empirical models as [UMT].

Experimentally the path loss $L_{path}$ in dB, can be calculated by

$$L_{path} = P_T - P_R + G_T + G_R$$  \hspace{1cm} (4.1)$$

Where $P$ is the received and transmitted power and $G$ is the antenna gain.

The shadowing or slow fading is caused because of the fact that the mobile terminal moves and some paths will suffer increased loss, while others will be less obstructed. The inclusion of shadowing into propagation models transforms the coverage radius of a cell from a fixed, predictable value into a statistical quantity. The properties of this quantity affect the coverage and capacity of a system in ways which can be predicted with a log-normal distribution function.
\[ f(P) = \frac{1}{\sigma_y \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left( \frac{P - \bar{P}}{\sigma_y} \right)^2 \right] \] (4.2)

Where \( \bar{P} \) is the mean value of power and \( \sigma_y \) is the standard deviation. Both are expressed in logarithmic units. The value of \( \bar{P} \) is predicted by the path loss empirical models and the \( \sigma_y \) by the environment.

It is also necessary to know the received power velocity of variation. This does not change instantaneously, due to the environment does not change instantaneously there is a time correlation between the signals. The value of the time correlation depends on the environment and the velocity of the mobile. Generally, it is used an exponential time correlation \([\text{GUD-91}]\)

\[ R(\tau) = e^{-\alpha \tau} \] (4.3)

The value of \( \alpha \) describes the variability of the signal and depends on the mobile velocity and the kind of environment.

Finally, the fast fading do significant variation in the received signal as the mobile moves over distances which are small compared with the shadowing correlation distance. This phenomenon varies so rapidly that it can only usefully be predicted by statistical means. This fading is described statistically by Rayleigh or Rice distributions with good accuracy, depending on whether non-line-of-sight or line-of-sight conditions prevail. Both cases degrade the signal quality relative to the static case, where the channel can be described by simpler additive white Gaussian noise statistics. The rate of variation of the fading signal, due to the phenomenon of Doppler spread, is controlled by the carrier frequency, the speed of the mobile and the angle-of-arrival distribution of waves at the mobile.
IV.3 Wideband Channel Parameters

The impulse response is a useful characterization of the channel, since it may be used to predict and compare the performance of many different mobile communication systems and transmission bandwidths for a particular mobile channel condition.

For a fixed position $d$, the channel between the transmitter and the receiver can be modeled as a linear time invariant system. However, due to the different multipath waves which have propagation delays which vary over different spatial locations of the receiver, the impulse of the linear time invariant channel should be a function of the position of the receiver. That is, the channel impulse response can be expressed as $h(t)$, $x(t)$ represent the transmitted signal, then the received signal $y(t)$ can be expressed as convolution of $x(t)$ with $h(t)$.

$$ y(t) = x(t) \ast h(t) = \int_{-\infty}^{\infty} x(\tau) h(t-\tau) d\tau $$  \hspace{1cm} (4.4)

$h(t)=0$ for $t<0$ in a causal system, so the equation above can be rewritten as:

$$ y(t) = \int_{0}^{t} x(\tau) h(t-\tau) d\tau $$  \hspace{1cm} (4.5)

For a multipath channel is normally used the discrete equation

$$ y[n] = \sum_{k} x[k] h[n-k] $$  \hspace{1cm} (4.7)

And the discrete impulse response is described as

$$ h[n] = \sum_{i=0}^{N-1} a_i \delta[n-i] $$  \hspace{1cm} (4.8)

where $a_i$ is the amplitude of the path, $N$ is the number of multipath components, and $\delta[n]$ is the Dirac delta function.
In wireless communications the mobile or the objects around are in movement. Therefore, the impulse response will vary with the time. The channel evolution is represented by the function $h(t, \tau)$.

The delay spread characterizes the echoes of the received signal. These echoes introduce time scattering, which produces frequency filtration, that is to say, two frequencies whose separation is superior to the inverse of the delay spread will suffer different attenuation. For against, if the frequency gap is less than the inverse of the delay spread, they will have a similar attenuation.

With the purpose of characterizing the channel and since the channel varies with the time, it is used the average of the impulses responses, it's called Power Delay Profile (PDP). Defined as:

$$P(\tau) = E\left\{ |h(\tau, t)|^2 \right\}$$  \hspace{1cm} (4.9)

Usually the PDP is discretised in the delay dimension to yield $n$ individual taps of power. Each tap-gain process may be Rice or Rayleigh distributed.

The PDP may be characterized by various parameters:

The mean excess delay $\tau_0$ is the first moment of the PDP.

$$\tau_0 = \frac{1}{P_T} \sum_{i=1}^{n} P_i \tau_i$$  \hspace{1cm} (4.10)

where the total power in the channel is

$$P_T = \sum_{i=1}^{n} P_i$$  \hspace{1cm} (4.11)

RMS delay spread, the second moment, or spread, of the taps; this takes into account the relative powers of the taps as well as their delays, making it a better indicator of system performance than other parameters; defined by

$$\tau_{RMS} = \sqrt{\frac{1}{P_T} \sum_{i=1}^{n} P_i \tau_i^2 - \tau_0^2}$$  \hspace{1cm} (4.12)
If the RMS delay spread is very much less than the symbol duration, no significant ISI is encountered and the channel may be assumed narrowband.

From the Fourier transform of the PDP is obtained the coherence bandwidth defined as the maximum bandwidth that can be transmitted by the channel without the multipath distortions affect significantly. It is defined as:

\[
B_c = \frac{1}{2\pi \tau_{\text{RMS}}}
\]  

(4.13)
V. REVERBERATION CHAMBER

V.1 Introduction

The *Reverberation Chamber* (RC), see Fig. 5.1, is a complex cavity of Faraday made by a shielded box, usually rectangular, containing some movable conducting structure called stirrer. The cavity should have a size that is in the order of 5-10 wavelengths ($\lambda$) in any dimension to support the assumption that the cavity is overmoded for the frequency that is used.

![Fig 5.1a, Bluetest reverberation chamber](image-url)

Figure 5.1b, Renault reverberation chamber, 221 m$^3$
Reverberation chambers provide an interesting environment for testing electronic systems against radiated electromagnetic fields. The RC test procedure offers advantages compared to conventional approaches (outdoor ranges, anechoic chambers). The most interesting aspects are time effective testing as well as lower equipment costs (amplifiers, antennas, facilities) due to reduced power requirements and the absence of absorbers. These aspects render RCs especially interesting for the test of large objects. Other great advantage is that can be used also for antenna measurements as it simulates effectively a uniform multi-path propagation environment.

Besides the aforementioned advantages, the RC method also pose some drawbacks, namely, the loss of input-angle dependent information, the loss of polarization control and the influence of losses in the device under test on the required excitation power levels.

The original problem was that in high frequencies, required power levels have entailed prohibitive testing costs if the test is carried out within an Anechoic Chamber (AC), a room in which there are no echoes, or a similar testing environment. It is shown that the reverberation chamber test method can be substituted for the anechoic chamber method thereby effectively solving this problem.

A qualitative comparison highlighting the advantages and disadvantages of EMC tests in reverberation chambers versus anechoic chambers is given in Table 5.1.

<table>
<thead>
<tr>
<th></th>
<th>Anechoic chamber</th>
<th>Reverberation chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical setup</td>
<td>-Shielded room</td>
<td>-Shielded room</td>
</tr>
<tr>
<td></td>
<td>-Absorbers</td>
<td>-Stirrers</td>
</tr>
<tr>
<td></td>
<td>-TX/RX antennas</td>
<td>-TX/RX antennas</td>
</tr>
<tr>
<td>Type of field</td>
<td>Plane wave/Single path</td>
<td>Multi mode/Multi path</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear, fixed</td>
<td>Arbitrary, not known</td>
</tr>
<tr>
<td>$\vec{E}$, $\vec{H}$ phase relation</td>
<td>Fixed</td>
<td>Not fixed</td>
</tr>
<tr>
<td>Direction of incidence</td>
<td>Known, fixed</td>
<td>All directions, “isotropic”</td>
</tr>
<tr>
<td>Field impedance</td>
<td>377 $\Omega$</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Numerical simulations of reverberation chamber

<table>
<thead>
<tr>
<th>equipment under test (EUT) radiation pattern</th>
<th>Assumptions:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- &quot;well-behaved&quot;</td>
</tr>
<tr>
<td></td>
<td>- &quot;dipole-like&quot;</td>
</tr>
<tr>
<td></td>
<td>No assumptions made</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission testing</th>
<th>- extensive scanning needed to get peak - one direction at a time</th>
<th>- &quot;integral approach&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- omnidirectional testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Immunity testing</th>
<th>- uncertainty about EUT directivity - one direction at a time</th>
<th>- &quot;isotropic approach&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- omnidirectional testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Simple</th>
<th>Elaborate</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test software</th>
<th>Simple, not mandatory</th>
<th>Complex, “mission critical”</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Production line testing</th>
<th>Slow, impossible</th>
<th>Fast, automated</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test repeatability</th>
<th>Bad (e.g. ±20 dB)</th>
<th>Good (e.g. ±3dB)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>High field strengths...</th>
<th>...need large amplifiers</th>
<th>...need small amplifiers</th>
</tr>
</thead>
</table>

Table 5.1: Basic differences between the Anechoic Chamber and Reverberation Chamber electromagnetic compatibility test environment (extracted from [13]).

V.2 Electric field characterization within a reverberation chamber

In the high-frequency asymptotic sense, the field at a point inside a cavity can be described as a superposition of ray fields originating from the transmitting antenna. Since the fields associated with the multiple-reflection of rays are dominant compared with the fields associated with the effects of diffraction (assuming the mode stirrer is electrically large), one can represent the cavity fields by the sum of the fields of the direct ray and multiply-reflected rays.

Thus, inside a general cavity the ray description of the electric field at an observation point (P) can be written as

$$E(P) = \sum_i E_i(P) \quad (5.1)$$

where $E_i(P)$ is the $i$th ray originating from the transmitting antenna and arriving at $P$ after experiencing a particular number of reflections defined in chapter III. Note that (5.1) is in general an infinite sum for a closed cavity and it must be truncated for computational purposes as discussed later.
The amplitude of one component of the electric field inside the chamber measured for a large number of different stirrer positions follows a Rayleigh distribution. The received power in an antenna will therefore follow the exponential distribution [10] and this is similar to a real propagation environment without presence of a direct propagation between the antennas. The environment inside the ideal reverberation chamber is also statistically isotropic and statistically uniform.

V.3 The stirrer

The stirrer or tuner is a complex shape metal paddle on the roof. The revolving stirrer changes the path lengths and the number of reflections of the waves as they arrive at a point. This entire means the magnitude at any point in the chamber is different from that at any other point and different at each tuner position. The stirrer also is used to stir the inevitable standing waves that occur inside the room. The stirrer should, as it moves, change the boundary conditions for the fields inside the cavity and thus create different mode structures inside the chamber.

The stirrer usually appears in the form of a paddle wheel, but a number of alternative methods of stirring have been proposed in the literature, e.g. frequency stirring [15], the moving wall mode-stirred chamber [16] and the vibrating intrinsic reverberation chamber (VIRC) [17].

An efficient stirrer will create a larger number of different mode structures than an inefficient stirrer and this will give a larger number of independent measurement samples and a smaller statistical uncertainty. The method that measures the effectiveness of the stirrer is called Stirring ratio.

a) Stirring ratio

The stirring ratio (SR) provides a global parameter to quantify changes of the field distribution induced by a rotating stirrer. It is commonly defined as

$$SR = \max P_{Re}(x_0, y_0, z_0) - \min P_{Re}(x_0, y_0, z_0)$$

(5.2)

which requires that the power received by an antenna within the reverberation chamber is measured over a certain number of stirrer angles at a fixed spatial
position. The input power is kept constant for all rotational stirrer angles. The SR is expressed in terms of decibels. A high stirring ratio suggests that both maximum and minimum E or H field values occur at the same position for different stirrer steps; this indicates a more effective stirrer. If the stirring ratio was measured at all points throughout the chamber, the optimal condition would be if it was uniform, as this would indicate that the stirrer was effectively changing the boundary conditions evenly throughout the chamber. The lower limit normally accepted for the stirring ratio is 20 dB.

b) Correlation stirrer coefficient.

A quantitative comparison of the stirrer performance is the correlation coefficient.

The correlation coefficient, $\rho_\phi(\varphi)$, where $\varphi$ is the angular "distance" between two stirrer positions, is calculated according to:

$$
\rho_\phi(\varphi) = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \langle x \rangle)(x_{i+\varphi} - \langle x \rangle) \frac{1}{\sigma_x^2} \quad (5.3)
$$

where $N$ is the total number of samples, i.e. the number of stirrer positions used to calculate $\rho_\phi(\varphi)$, $\langle x \rangle$ is the corresponding arithmetic mean value of these ensemble. It is defined as

$$
\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} (x_i) \quad (5.4)
$$

And $\sigma_x^2$ is the variance of the ensemble

$$
\sigma_x = \frac{1}{N-1} \sum_{i=1}^{N} [x_i - \langle x \rangle]^2 \quad (5.5)
$$

The correlation function can assume any value $|\rho_\phi(\varphi)| \leq 1$, with values of $|\rho_\phi(\varphi)| \approx 1$ indicating a good linear correlation and values of $|\rho_\phi(\varphi)| \approx 1$ little or no correlation at all. Applied to reverberation chambers, $\rho_\phi(\varphi)$ relates e.g. the magnitude of the
electric field at a fixed position \((x_0, y_0, z_0)\) for the angular position \(\varphi_1\) of the tuner against the magnitude of the same electric field at the same location for the angular position \(\varphi_2\). The calculation of the correlation allows a quantitative comparison of the stirrer performance. For a well-operating reverberation chamber, a low correlation between the EM fields obtained at the two angular stirrer positions \(\varphi_1, \varphi_2\) is desirable.

In [18] the correlation coefficient \(\rho_0(\varphi)\) calculated from the magnitude of the electric field \(|E|\). Each data point in Figs. 5.4 corresponds to the correlation between the simulated \(|E|\) for the reference stirrer angle \(\varphi = 0^\circ\) and \(|E|\) for \(\varphi = 0^\circ\ldots355^\circ\). Fig. 5.2 compares \(|\rho_0(\varphi)|\) for four stirrers, shown in figure 5.2 and 5.3.

![Fig 5.2, Vertical stirrer models: "6-paddle stirrer" & "cross-plate stirrer"
Fig 5.3, Vertical Z-fold stirrer]
Numerical simulations of reverberation chamber

Figure 5.4, Absolute value of the correlation coefficient $|\rho_0(\varphi)|$ as a function of stirrer angle $\varphi$ at a frequency $f = 300$MHz

Initially (for $\varphi = 0^\circ$…$60^\circ$) the correlation $|\rho_0(\varphi)|$ drops rapidly for all stirrers, which indicates that they are electrically sufficiently large in order to achieve substantial changes of the field pattern within the RC. For both the 6-paddle and the Z-fold stirrer $|\rho_0(\varphi)|$ remains relatively small (with some oscillations), whereas the cross-plate stirrer reaches $|\rho_0(\varphi)| = 1$ again at $\varphi = 180^\circ$, which is due to its rotational symmetry.

It is known that at low frequencies (around $f = 100$MHz) the overall correlation is high. This is due to the fact that any intentional rotational asymmetry is too small compared to the wavelength. At higher frequencies the correlation improves.

V.4 Q-factor

The quality factor $Q$ describes the ability of a system to store energy. This $Q$ factor is independent of the antenna radiation pattern inside a reverberation chamber. A high $Q$ indicates that a reverberation chamber has low losses and is therefore very efficient in storing energy. The chamber $Q$ is an important quantity because it allows prediction of the mean field strength resulting for a given input power. In addition, it provides an estimate of the chamber shielding effectiveness and the reverberation chamber time constant.
The classical definition of $Q$ for a single frequency of operation $\omega$ at steady state is given by

$$Q = \omega \frac{U_r}{P_d}$$  \hspace{1cm} (5.6)

with $P_d$ being the dissipated power. The total stored energy $U_r$ can be computed from

$$U_r = \frac{1}{2} \iiint_V \bar{D} \cdot \bar{E} \, dv = \frac{1}{2} \iiint_V \left| \bar{E} \right|^2 \, dv$$  \hspace{1cm} (5.7)

Expression (5.6) can be further reduced for typical dimensions and wavelengths $\lambda \leq 1\text{m}$ to

$$Q \approx \frac{3V}{2\mu_0\delta A}$$  \hspace{1cm} (5.8)

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \text{Skin depth}$$  \hspace{1cm} (5.9)

Where $\mu_r = \frac{\mu}{\mu_0}$ is the relative permeability of the cavity wall, $V$ is the volume, and $A$ is the inner surface area of the cavity.

When the reverberation chamber is simulated or measured, the $Q$-factor can be determined by measurements. $Q$-factor measurements in RCs are commonly carried out with a transmitter and receiver antenna inside the chamber and recording the received and transmitted power [11]. Using this approach, the chamber quality factor $Q$ can be estimated as

$$Q = \frac{16\pi^2 V P_r}{\lambda^3 P_T}$$  \hspace{1cm} (5.10)

A time constant was suggested in [11] defined by
\[ \tau = \frac{Q}{\omega} \]  
(5.11)

which determines the exponential decay rate of the stored energy when the source is suddenly turned off. Since the same \( \tau \) applies to the case of energy build-up when the source is suddenly turned on, it can be written that

\[ U_T(t \geq 0) = U_s (1 - e^{-\frac{t}{\tau}}) \]  
(5.12)

It is of interest to extract numerically using the ray method presented here. However, to extract directly using (5.11), one would have to compute the total stored energy as a function of time, which would require integrating the field over the entire volume of the chamber at each time step. Supposing that the numerical sampling is on the order of a fraction of a wavelength, a numerical integration scheme becomes impractical for electrically large cavities.

The relationship (5.11) is valid as long as the Q factor is sufficiently high [12].

V.5 Early-time field approximation

It is found that the ray solution cannot predict the steady-state fields of high-Q enclosures because of the intractably large number of ray reflections required for convergence; the rays would have to be tracked through thousands of reflections from the chamber walls to reach a convergent solution.

However, it is demonstrated in [11] that the steady-state Q factor may be predicted from the early-time energy density build up at a point by coherently summing the power in each ray. The Q factor is obtained via its relationship to the cavity time constant \( \tau \) (5.11), which may be extracted from the early-time energy density curve. The advantage of the ray method is that it can be used to treat large closed cavities of relatively arbitrary shape.

As I said before, the time constant \( \tau \) cannot be extracted from the equation (5.12), however, if one sums the power in the rays using magnitude only, the energy density build-up at a point may be written as
\[ D_p(t) = \sum_{i} |E_i(P)|^2 u \left( t - \frac{R_i}{c} \right) \]  

(5.13)

Where \( R_i \) denotes the total path length of the \( i \)th ray. The energy density build-up is expected to have a behavior similar to (5.12).

\[ D_p(t \geq 0) = D_0 \left( 1 - e^{-\frac{(t-t_d)}{\tau}} \right) \]  

(5.14)

where the time delay \( t_d \) has been introduced because unlike \( U_p(t) \), \( D_p(t) \) stays at zero until the first ray arrives at the receiver.

In the same manner, the electric field is expected to have a behavior similar to the others.

\[ E(t \geq 0) = E_0 \left( 1 - e^{-\frac{(t-t_d)}{\tau}} \right) \]  

(5.15)

**V.6 Convergence of the Reverberation Chambers**

As said before, the steady-state fields cannot be directly computed since the rays would have to be tracked through thousands of reflections from the chamber walls to reach a convergent solution. This chapter will describe how many paths arrive per time and how affect the material and his conductivity.

First of all, the number of images contributing to the Electric field at time \( t \) in a chamber of volume \( V \) is

\[ N = \frac{4}{3} \pi (t c)^3 / V \]  

(5.16)

The minimum number of reflections required for convergence depends of the chamber material. The work [11] shows that the field reaches its steady-state value after a time when all the subsequent rays are attenuated by reflections to less than 6/10 of their free-space magnitude. The minimum number of reflections \( n \) required for convergence may then be calculated approximately from:
\[ |R_{\perp\perp}\left(\theta_i = 0\right)|^n = 0.6 \] 

(5.17)

Where \( n \) is the number of reflections, \( R \) is the reflection coefficients, which relates the reflected field components to the incident components and is defined in the chapter III, concretely the equation 3.5.

The example is based on a chamber of \( H = 2.24 \text{ m}, L = 2.92 \text{ m}, l = 2 \text{ m}, V = 13\text{m}^3 \) with a modulation frequency of 5 GHz. The same used at the simulations.

<table>
<thead>
<tr>
<th>( \sigma ) (S/m)</th>
<th>( 10^2 )</th>
<th>( 10^3 )</th>
<th>( 10^4 )</th>
<th>( 10^5 )</th>
<th>( 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}^\text{o} ) of Paths</td>
<td>( 10^5 )</td>
<td>( 10^6 )</td>
<td>( 10^7 )</td>
<td>( 10^8 )</td>
<td>( 10^9 )</td>
</tr>
<tr>
<td>( \text{N}^\text{o} ) of Reflections</td>
<td>48</td>
<td>153</td>
<td>485</td>
<td>1532</td>
<td>4846</td>
</tr>
<tr>
<td>Settle time (( \mu\text{s} ))</td>
<td>0.22</td>
<td>0.48</td>
<td>1.04</td>
<td>4.83</td>
<td>22.37</td>
</tr>
</tbody>
</table>

Table 5.1 Comparison of No. of Paths and No. of Reflections required for Steady-State Convergence.
VI. Electromagnetic Simulation

VI.1 Introduction

Today, electromagnetic (EM) field-solvers have given the radio frequency (RF) or high-speed digital design engineer new tools to attack more difficult design problems. Used often in conjunction with circuit-theory-based CAD, these new tools generate solutions derived directly from Maxwell’s equation.

But with the field-solver, we also have the capability to look inside the structure and display surface currents, various types of electric-field and magnetic-field plots, or other quantities derived from the fields.

By the mid-1990s, faster computers and more efficient software made it possible to optimize planar and three-dimensional (3D) RF structures using direct driven electromagnetic simulation. Although practical problem size is still limited, field-solver tools can now be more fully integrated into the design environment.

While theory and experiment remain the two traditional pillars of science and engineering, numerical modeling and simulation represent a third pillar that supports, complements, and sometimes replaces them.

In this chapter, the predominant methods used in computational electromagnetics will be discussed. They determine the properties of the numerical “engines” of the various commercial simulators and define their respective characteristics, strengths, and limitations.

The range of applications of the electromagnetisme is reflected by the broad variety of numerical methods. The main classification could be the table 6.1
<table>
<thead>
<tr>
<th>Method Type</th>
<th>Description</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential methods</td>
<td>Accurate and easy to implement but limited when complex geometries are treated</td>
<td>FDTD-Finite Difference Time Domain, FDFD-Finite Difference Frequency Domain</td>
</tr>
<tr>
<td>Varational methods</td>
<td>Precise and excellent with complex geometries but computationally intensive</td>
<td>MoM-Method of Moments, BEM-Boundary Element Method, FEM-Finite Element Method</td>
</tr>
<tr>
<td>Hybrids methods</td>
<td>Mixture of two or more methods, it has the advantages of combining the most characteristic parts of each method and minimize their weaknesses</td>
<td>FEM-MoM, FDTD-FEM, GTD-FEM</td>
</tr>
</tbody>
</table>

Table 6.1: Numerical methods

Of all simulation methods we are going to use the FDTD (Finite Discrete Time Domain), due to the fact that it is the better for high frequencies, and can model an arbitrary cavity.

The XGTD theory is shown in annex B.
PART II

COMPUTATIONAL RESULTS
VII. THE FIRST SIMULATION CHAMBER

VII.1 Introduction

Once having familiarized with the reverberation chamber theory and the simulation software, we started to test the software. The goal is to determine the software parameters to get a model similar to the reality.

Firstly, the optimal number of reflections, diffractions and transmissions must be obtained. The maximum number of reflections and transmissions is 30. The user should be aware that the run time will increase as these numbers grow and, in some cases, it may increase dramatically. There is also a limit on the maximum number of diffractions depending of the model. It should be noted that including additional diffractions can dramatically increase run time, even more so than adding additional reflections and transmissions.

At this chapter, reflections and diffractions are studied and compared with the simulation time since stable results are obtained. Due to the chamber and the objects are perfect electrical conductors no transmissions are studied. The door, cables, noise or interferences are not simulated.

Finally, the power received, the impulse response, the Q-factor and the stirring ratio are studied and compared with empirical results from literature.

VII.2 The chamber

Figure 7.1 shows the first model of a reverberation chamber. The transverse dimensions are H= 2.24 m, L= 2.92 m, l= 2 m. The stirrer is a cross-plate stirrer with two rectangular plates of equal size that intersect at an angle of 90°. The plates measure 1m x 1m. The stirrer is situated in the ceiling, in the middle of the chamber. The stirrer has an angular step of 1°, so we will have 45 different situations.
The walls as well as the objects are of a PEC material. This is a good but not completely real situation, in further studies the material will be aluminium, cooper and absorber.

![3D view of the chamber](image)

**Fig. 7.1; 3D view of the chamber**

Both antennas are situated on the “y axis” and separated 2 meters, (x=1, y=0) and (-1, 0), being (0,0) the center of the chamber. The antennas are raised 0.1 and 0.5 meters to get reflections with the floor.

To obtain NLOS, we could use directional antennas directed to the wall o to the corner, but omnidirectional antennas will be used to get the biggest number of reflections with the chamber and the stirrer. Because of that, we must use another way to get NLOS; the way to get it is to put a metallic wall between the transmitter and the receiver. This wall is in the middle of the chamber and has a height of 0.75m.

The transmitter and the receiver are identical antennas, omnidirectional, vertical polarization, 0dB gain and designed for 5 GHz.

The waveform is a sinusoid of frequency 5 GHz and 10 MHz of Bandwidth. During all the simulations the frequency will not change. The output transiting power is 0dBm.

As the antennas are fixed and we will not change the working frequency, the only change will be caused by the angular movement of the stirrer.
VII.3 Parameters Of Simulation

The number of paths chosen is 30. The starting value was 25, the received power rises until 30 paths, and then the power received keeps stable.

To choose the number of reflections, with 1 diffraction, we start with 6 reflections, as we increase the number of reflections; we observe a rise of the time of simulation. With only 6 reflections we can see that we lose reflections with the stirrer that affects the final result. From the 7th the difference oscillates $\pm 0.6\text{dBm}$.

![Figure 7.2. Variations with the number of reflections](image1)

![Figure 7.3. Variations with the number of Diffractions.](image2)
To get a good analysis and the lower time of simulation we chose 1 diffraction. Starting without diffractions and ending in 7, we see that the time of simulation rises with the first diffraction and becomes constant between 1 and 7. Although the difference between the values is 2dB, the greater part are between -36.6dBm and -37dBm. Therefore, 1 diffractions are chosen.

**VII.4 Outputs**

To choose the parameters the antennas were 10cm over the floor, for the final simulations the antennas are 50 cm over the floor to get more reflections with the floor. With elevation we lose some dB.

a. The power received

Since the antenna emits 0dbm and there is no gain, the received power is the path loss. As was expected we can see in figure 7.4 that on 0° there is a minimum of reception, because the stirrer blocks the transmission as a wall. There is another aberrant minimum in 33°. Studying the paths for this angle we can see that the result differs with the power received by the neighbors because we lose one of the most important paths.

![Figure 7.4. Variation of amplitude versus the position of the stirrer](image)

The average is -42.71dBm, lower than expected.

The power received will be useful to get the Q factor and the Stirring Ratio.
b. The impulse response.

A very useful characteristic of the statistical channel properties is its impulse response. As the number of reflections is limited we cannot see a fall of amplitude with the delay. For further simulations will be good use a bigger number of reflections and a statistical average of the impulse response.

The impulse response has NLOS characteristics, the first paths arrive about 16ns, and the higher paths arrive about 20ns, and start descending. The impulse response is cut because we don’t have enough reflections simulated to know what happens after 40ns.

As we can see in figure 7.5, the first paths arrive from diffractions with the wall so we can see that they are fewer than the others that arrive with reflections, which arrive later.

![Image of impulse response](image)

**Figure 7.5:** Example of impulse response of the chamber
c. Q-Factor

Once a Reverberation Chamber is simulated, the chamber-Q can be determined by the measurements. The Q-factor of the camber is calculated using the equation 5.9.

As the mean value of the coupling factor <Pt/Pr> being equal to 42.71dB lead to <Q> = 650. This value is lower than those reported in the literature.

d. Stirring Ratio

The stirring ratio (SR) provides a global parameter to quantify changes of the field distribution induced by a rotating stirrer. The Stirring Ratio is obtained with the equation 5.2

\[
SR = P(15^\circ) - P(33^\circ) = -37.33\text{dBm} + 57.69\text{dBm} = 20.36\text{dB}
\]

This is a good result for a Reverberation chamber, because the stirrer changes the scenario, but considering the result of 33° aberrant and the 0° trivial, the Stirring Ratio is:

\[
SR = P(15^\circ) - P(39^\circ) = -37.33\text{dBm} + 47.33\text{dBm} = 10.00\text{dB}
\]

The result is not as good as the first but it is acceptable, that confirms that the stirrer is quite simple.

VII.5 Conclusions

If we examine the chamber and the paths we can see that only one diffraction is possible, there will be a diffraction with the wall or with the stirrer. There could be one path with two diffractions, but his energy will be much smaller than others that arrive with reflections. That's why in figure 7.3 the time of simulation does not increase with 2 or more diffractions, simply, the software does not consider more than one.

At this first approach we can see that impulse response ends earlier than is supposed. Since very little power is dissipated when a wave reflects from the
highly conducting walls, the statistical and empirical methods suggest that the antenna will receive relevant paths during approximately 200ns. With these parameters only the early-time paths are simulated.

The next steep was to simulate the chamber with higher number paths, a more complex stirrer and the wall and the stirrer material will be changed for one realer.
VIII. COMPLEX STIRRER SIMULATION CHAMBER

VIII.1 Introduction

The second step is to improve the reverberation chamber model. Although some previous works use a perfect electrical conductor material to simulate reverberation chambers and high reflective environments as airplanes, for a realistic simulation the wall and objects conductivity must be considered.

To get better results the stirrer is perfected, a more complex stirrer modifies the transmission paths and it is expected to allow more reflections and new channel conditions at each angle, as shown in section V.3.

As seen before, the number of paths of the previous scenario doesn’t seem to be enough to get the steady-state field. This time, the maximum number of reflections and paths will be used.

VIII.2 The camber

The new chamber has the same dimensions that the last one (H= 2.24 m, L= 2.92 m, l= 2 m). The wall is not a sheet, now it has three dimensions, 20 cm of width (figure 8.1).

The stirrer is replica of the stirrer physically existing in the prototype RC of the Defense Science and Technology Organization (DSTO) of Australia, figure 8.2. It consists of four rectangular paddles of size 0.60m x 0.60m, rotationally offset by 60° with a slanting angle of 45° for each paddle. The stirrer rod, which supports the paddles, is not simulated as it was found to be electromagnetically irrelevant.

Now, the receiver antenna is placed at a corner to obtain more reflections from the wall, also it will break the symmetry and more independent samples could be obtained with the stirrer rotation.

The main materials used for construction of RCs are usually galvanized steel, aluminum, and copper. The values of the materials are obtained from the “Materials database of the National Institute of Standards and Technology” [19].
For the aluminum structure of the stirrer and the wall, the tabulated value is \( \sigma = 27 \, \epsilon 06 \, \text{S/m} \).

\[ \sigma = 27 \, \epsilon 06 \, \text{S/m} \]

**Figure 8.1**, 3D view of the second chamber

**Figure 8.2**, 4-paddle stirrer

### VIII.3 Parameters Of Simulation

Now the parameters are chosen to obtain the maximum number of paths. The maximum number of paths simulated chosen is 10e06.

The maximum number of reflections accepted by the software is 30, but with 30 reflections we have a very few number of paths, only 60, and looking at the paths, we the ray with more reflections has 7 reflections. When we reduce the maximum number of reflections, more paths and more reflections are obtained; playing with the numbers, the best number of reflections is 15, with 113 paths.

The number of received rays can be limited by the antenna resolution. The proper setting for the ray spacing depends on several factors. As the XGTD manuals [20] says, “as a rule of thumb, for a 500 m x 500 m area, use an angular spacing between rays of least 0.2 degrees. The angular spacing should be decreased in
inverse proportion to the size of the area of the chamber”. Since the chamber is smaller and there are fine geometric features we may require more resolution.

With the ray spacing of the antenna set at 0.1° the antenna simulation will emit 
\[ (360°/0.1°) \times (180°/0.1°) = 6.48 \times 10^6 \] paths, due to the fact that XGTD uses the spherical coordinate system [1], with [0..360°] for \( \phi \) and [0..180°] for \( \theta \). Obviously not every path will arrive to the receptor, so, we have only 113 paths (15 reflexions). Making the ray spacing smaller (0.05°) we have 
\[ (360°/0.05°) \times (180°/0.05°) = 25.92 \times 10^6 \] simulated paths, and 128 arrives to the receiver, smaller ray spacing than 0.05 takes long time simulations and no result.

In the last model the first paths have one diffraction, but the new model, since the wall is not a sheet, these diffractions don’t appear. Setting the number of diffractions to 1, 2, the number of paths simulated decreases considerably because of the software limit; from 113 to 91 paths and the maximum number of reflections are 10. Moreover, the time simulation rises considerably. In conclusion, watching the simulation paths there is no diffraction, so in this model no diffractions are considered.

There are always a constant number of paths at the receiver; the stirrer doesn’t limit the number of paths arriving to the antenna, the software do.

**VIII.4 Outputs**

With 15 reflections and 128 paths, the results finish between 25 and 30ns depending of the stirrer position. After that, there are no new paths. In spite of that, as it is shown in section V.4, some parameters as the Q-factor can be extracted from the early field.

The average of the electric field with 2373 points and 180 different stirrer positions (one revolution) is shown in figure (blue draw). Due it is modulated by a sinus a mobile average of 10 samples is applied to get the equation (5.15) (red draw).

From 40ns, not enough samples are available, so these results are omitted.
In figure 8.4 the graph seems to have a behavior similar to the classical exponential model, therefore, getting the exponential parameters with Excel solver, two approximations are obtained, in blue the one which approximates the beginning—equation 8.1—, and in yellow the one which approximates the steady-state—equation 8.2—.

Figure 8.4: Exponential model approximations.
Numerical simulations of reverberation chamber

\[ Etot = 1.77(1 - e^{-\frac{t}{1.268 \times 10^{-9}}}) \]

(8.1)

\[ Etot = 2.05(1 - e^{-\frac{t}{10.73 \times 10^{-9}}}) \]

(8.2)

These approximations don’t seem to be enough good, as the Excel determination parameter \( R^2 \) - a parameter that determines how good is the approximation, from 0 (very bad) to 1 (the same graph) - the first approximation has an \( R^2 = 0.69 \) and the second \( R^2 = 0.75 \).

Apparently, the electric has a constant slope and could correspond therefore to a lineal approximation. In figure 8.5 the lineal approximation –equation 8.3- is presented and can be seen that it fits better than the exponential approximations. The determination parameter is \( R^2 = 0.97 \)

\[ Etot = 0.98 \times 10^9 (t - 8.38 \times 10^{-9}) \quad 0 < t < 2.682 \times 10^{-8} \]  

(8.3a)

\[ Etot = 18.071 \quad t \geq 2.682 \times 10^{-8} \]  

(8.3a)

![Figure 8.5 Lineal model approximation.](image)
Consequently, the electric field simulated is only the early-time field, and not the steady-state field. At 26.82ns the last path arrives and the electric field is constant. In spite of this, the Q-factor can be obtained with the 5.15 & 5.11.

With \( \tau = 11.268 \times 10^{-9} \); \( Q = \frac{\omega \cdot \tau}{5 \cdot 10^9 \cdot 11.268 \times 10^{-9}} = 353.99 \)

The Q-factor is far away of those reported in the literature" \( Q \approx 10^4 \)"[21], the path loss now is -35dBm –fewer than expected–, so we have the same problem as the last scenario, not enough paths (figure 8.6). And the new stirrer increase the simulation time, but don’t improve the stirring-ratio.

![Figure 8.6: Complex impulse response of the chamber](image)

**VIII.5 Conclusions**

The second scenario introduces some improvements. The stirrer adds complexity to the chamber; the walls and the stirrer conductivity make it realer. And the increment of reflections and paths give us more information.

In spite of the improvements the simulation continues stopping very early, therefore many paths with significant power are lost.
From this experiment we learn more about the limitations of the software: the maximum number of paths is 200, but it is limited by the complexity of the scenario and reflections, that is important to know what is capable and what is not capable to do.

Unfortunately, we don’t have more than the very early-field and the first arrival paths. These are so few that we are not able to make the early-field approach.

Other writers had the same problem and decide to put absorbers or decrease the conductivity of the chamber. In the next scenario will be studied the advantages and disadvantages of reducing the conductivity and, therefore the Q-factor.
IX. LOW CONDUCTIVITY CHAMBER

IX.1 Introduction

It is showed that achieving stability in an FDTD code can be very difficult for high-Q devices such as RCs [22, 23]. In these simulations, the conductivity of the chamber walls is reduced to physically unrealistic values (e.g. \( \sigma < 100 \) S/m) in order to achieve convergence. Furthermore there are introduced artificial losses in the air volume within the RC to improve the convergence speed. Also F. Petit’s FDTD simulations make use of somewhat inappropriate conductivities on the order of \( \sigma = 100 \) S/m for metallic surfaces [24].

Two conductivities will be studied, the real aluminium conductivity, \( \sigma = 27 \cdot 10^6 \) S/m, a low-Q chamber \( \sigma = 100 \) S/m. It is seen that with a high conductivity the software only simulate the early-field, with the low-Q conductivity the results obtained can be compared with a loaded reverberation chamber.

IX.2 The chamber

As the replica stirrer adds complexity to the system that increase the time of simulation and do not give better results, for this simulation will be used the cross-plate stirrer with two rectangular plates of 1m x 1m, that intersect at an angle of 90º.

Figure 9.1, 3D view of the second chamber
The transmitter and the receiver are placed as the second scenario, the transmitter centered and the receiver at a corner to obtain reflections from the wall and to break the symmetry. The ORiNOCO AP 2000 is the access point simulated in the present chapter [25]. The transmitter emits at 5GHz, 17dBm with a gain of 3dBi, and the receiver has a gain of 2dBi. This will not modify the reverberation chamber parameters, due, as said before; these parameters depend of the chamber and don’t depend of the antenna.

IX.3 Outputs

Now we will simulate the wall of the chamber for two materials, the stirrer continues with $\sigma=27e06$ S/m. In figure 8.2 illustrates that in the lossiest case, with $\sigma=100$ S/m, the filed reaches steady-state relatively early, while the realistic case of $\sigma=27e06$ S/m, convergence could not be reached.

![Electric Field vs Time Graph](image.png)

Figure 9.2, The mean envelope of electric fields versus time
As we can see in figure 9.3 the only difference between the two scenarios is 10dB. That was the expected result, as the loss of conductivity will introduce a loss of received power.

The stirrer works well, as the stirring ratio is about 12dB in both cases.

![Figure 9.3: Simulation of the receiver’s power vs. stirrer degree](image)

Now it seems to be possible to obtain the Q parameter. The exponential approximation with $\sigma=100$ S/m, is $Etot = 0.5 \times (1-e^{-t/6.19e-9})$. With $\sigma=27e06$ S/m it doesn’t seem to be stable it rises lineal until arrives to the maximum number of paths, then it stops rising, the exponential approximation is $Etot = 1.2 \times (1-e^{-t/5.56e-9})$.

To get the Q parameter it is used the Received power formula (5.10) and the Curve tendency approximation (5.11). In addition, it is included a third approximation extracted from [5]. This paper shows that the time constant $\tau$ is also the delay spread.

The results are summarized in table 9.1 and 9.2
At this point, the results are not as good as it was expected. Now the problem is that the $\tau$ approximation is only good with a high Q [12], and when I decrease the conductivity, the reflections decrease and Q parameter decreases. With $\sigma = 27 \times 10^6$ (S/m) the Q is enough big to have a good approximation, but the software stops the paths very early, so an stable electric field cannot be obtained and the $\tau$ is not good approximated.

Neither the Q-factor nor received power can be simulated with XGTD inside a reverberation chamber. On the other hand, the first paths are properly simulated; therefore some other parameters like the direction of arrival (DoA) and the direction of departure (DoD). Also, the first nanoseconds of the complex impulse response of the channel can be simulated.

Finally it is proved that the time constant $\tau$ of the electric field curve can obtained by the delay spread.
X. EMPIRICAL MODEL OF A ENGINE COMPARTMENT

X.1 Introduction

To validate the parameters of the software inside a real environment, it is useful to consider a simple scenario as the engine compartment. The model is studied in [9].

X.2 Engine compartment model

As showed in figure 10.1, the model is a closed box that simulates the engine compartment of a car, with the engine (large block) and the battery (small block). Both, the engine and the battery don’t allow transmissions.

![Figure 10.1 Model of engine compartment](image)

The prediction of the power received will be also measured for a several points, in spite of the fact that the simulation model cannot be compared with the real environment (as the real engine compartment contains much more complex objects, which produces scattering and fading that cannot be accurately simulated), it can be used to have an idea of the mean received power for LOS and NLOS antenna. As in [9] a transmitter power of -10dBm was used.

X.3 Simulation parameters

First of all the material must be choosen. As shown before the conductivity is a critical parameter for the XGTD simulations.
The walls will be of aluminium with a conductivity of 27E03 S/m. The pure aluminium conductivity is 27E06 S/m, but the real car's material is not pure aluminium, so 27E03 S/m is a good approximation and fits with the results of the literature.

This time, the simulation doesn’t need so many reflections as the reverberation chamber. As shown in table 10.1 showing the number of reflections and the diffractions the best number of reflections and diffractions is between 6 reflections and 0, 1 or 2 diffractions. With 6 and 7 reflections we have the maximum number of paths that allows the software (200); if we use more than 7 reflections we lose paths.

The Table 10.1 shows the results I obtained.

<table>
<thead>
<tr>
<th># reflections</th>
<th># diffractions</th>
<th>Received Power (dBm)</th>
<th># Paths</th>
<th>Time of simulation (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LOS</td>
<td>NLOS</td>
<td>LOS</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-42.55</td>
<td>-56.86</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>-39.73</td>
<td>-51.60</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>-38.04</td>
<td>-48.15</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>-37.32</td>
<td>-44.85</td>
<td>82</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-36.58</td>
<td>-42.00</td>
<td>140</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>-36.09</td>
<td>-40.12</td>
<td>200</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>-36.26</td>
<td>-38.65</td>
<td>200</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-36.36</td>
<td>-38.80</td>
<td>192</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-41.79</td>
<td>-53.62</td>
<td>53</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-39.32</td>
<td>-50.84</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-37.47</td>
<td>-45.26</td>
<td>131</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>-36.89</td>
<td>-43.52</td>
<td>143</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>-36.23</td>
<td>-40.97</td>
<td>169</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-36.05</td>
<td>-39.74</td>
<td>190</td>
</tr>
<tr>
<td>7</td>
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<td>-36.42</td>
<td>-39.10</td>
<td>172</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>-36.45</td>
<td>-39.09</td>
<td>172</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>-36.23</td>
<td>-41.04</td>
<td>166</td>
</tr>
</tbody>
</table>

Table 10.1: Difference between simulations depending on the number of reflections/diffractions
Some papers that study the influence of the number of reflections consider that more than 4 reflections do not appear to be required. Even [27] uses only 2 reflections or the combination reflection and diffraction.

With XGTD, considering the time of simulation, the number of paths and the power received 7 reflections with 0 diffractions, 6 reflections with 1 diffraction, and 6 reflections with 2 diffractions are the best parameters.

The diffractions adds complexity, increases the time of simulation and reduces the number of paths that the software is able to show.

To know if the diffractions affect the received power, with 4 and 6 reflections it is compared the power received at a line of 141 points, placed as can be seen in Figure 10.2. We can see that the received power doesn’t change excessively with and without diffractions, but the time of simulation is 6 and 8 times bigger. Therefore diffractions are not simulated at the engine compartment model.

\[\text{Figure 10.2: Line of receivers}\]

\[\text{Figure 10.3: Simulation of the receiver’s line with 6 reflections}\]

\[\text{Figure 10.4: Simulation of the receiver’s line with 4 reflections}\]
In situation of reverberation chamber, where the model is very accurate, it is possible to compute the individual ray path contributions under consideration of the phase. This is very important, as a large number of interactions must be taken into account due to the low reflection and diffraction losses of the materials utilized. On the other hand, in the car environments the model is usually simplified and inaccurate due to it would be very complicated to accurately model all the lossy/dielectric structures that compose the automobile structure (seats, interior trim, etc.). The phase of the signal contributions of different propagation paths is not considered for these environments, as the geometrical inaccuracies might be in the range of several wavelengths.

In Figures 10.5-10.8, the software shows the difference between the received power founded by adding the power of each path and the phase difference between rays is ignored, and the received power when all fields are summed with phase.

We can see that the phase consideration affects the received power received; strong attenuations are obtained at certain points in excess of 30dB. These attenuations are due to the interference effects caused by the phase.
As said before the phase will not be considered as it would lead to very specific results.

**X.4 Parameters validation**

Using only 2 reflections the paper [9] gets an impulse response of 21 paths that finish at 14ns (figures 10.11 and 10.12). This paper uses 2 reflections to keep the ray display concise, when I try to make the same with XGTD I get also 21 paths for the LOS antenna and 4 for the NLOS antenna, but my software don’t display the ray concise and we have 21 paths very close to the first ray. With 7 reflections we have more paths and the impulse response is longer on time (14ns).
These results show that environments with few reflections can be well simulated with this software. These parameters will be used for the next steep, the car model.
XI. MODELING IN-VEHICLE WIRELESS CHANNEL

XI.1 Introduction

The aim of the last part thesis is to characterize the wireless channel inside a car and compare the reverberation chamber wideband parameters, which is very original compared to existing literature.

The results of a measurement campaign are needed to validate the proposed ray model. In [5], an empirical channel studio is done and the in-vehicle parameters are compared to the reverberation chamber ones.

In order to describe the wideband channel, the received power is one of the most studied parameters; as it is a confined and reflective environment, the received power is supposed to be sufficient at every point. Other parameters, like the Impulse response, the PDP, the RMS Delay Spread or the Q factor are essential to know the available bandwidth, the presence of frequency fading, the maximum traffic rate or the presence of ISI.

The propagation ray data allow to analyze the individual propagation rays and thus to help understand the effects that occur in the car. It can also be used to evaluate the direction of arrival or departure; this information is helpful for the optimization of antennas if they are fixed, for example, vehicles sensors.

In fact, even if the car is a confined and reflective environment, the presence of seats, plastics and as studied in [6], passengers is an important factor to consider, as they tend to change the propagation path of a signal and a significant amount of power is absorbed and not reflected. Nowadays, the glasses inside cars are composed of a thin metal sheet to protect from solar illumination increasing therefore the reflections of the glasses and windshield, so reflective and non-reflective glasses should be considered.
XI.2 Opel Meriva empirical model.

The car used in the simulations and [5] measurements is an Opel Meriva [7]. The inner volume of the car is approximately $3.5m^3$. In order to measure the channel inside the car, two scenarios are considerate. The transmit antenna is placed on the dashboard while the antenna is placed behind the passenger front seat (Non line of sight - NLOS) and in the central back position (Line of sight – LOS). Since the car is empty, the channel is almost static for a given position. The environment around the exterior of the car was also static.

- Power delay profile (PDP)

![Figure 11.1](image)

As can be seen if figure 11.1, the PDP has a constant slope in dB and corresponds to a classical exponential model. This model has been shown to be well suited to characterize diffuse scattering [8]. In the car, there is no important specular path and the presence of many objects and reflections let us believe that the diffuse scattering propagation is an important contribution.

- The mean path loss

The mean path loss for every point of the grid was computed showing approximately the same average received power. The mean path loss is $-41.38$ dB.
- RMS Delay Spread

The rms delay spread has been estimated for each scenario. The results are shown in table 11.1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>RMS Delay Spread [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLOS</td>
<td>10.99</td>
</tr>
<tr>
<td>LOS</td>
<td>11.63</td>
</tr>
</tbody>
</table>

Table 11.1 RMS Delay Spread for each scenario

**XI.3 Pre-processing**

**XI.3.1 Reducing the complexity of the accurate model**

Generally, the first step involves designing the geometry but, in this case, it has already been designed, the model used is the “DOSCH 3D: Cars 2006”. However, for triangulate and simplifying geometry the AutoCAD and XGTD program is used.

The excessive detail sometimes included in DXF files can considerably increase computational time, and in some cases even produces less accurate results. XGTD contains an automated Simplify Feature capable of simplifying and cleaning up imported object files, putting them in the form required by the propagation model.

Here the car design is shown before the simplification:

![Figure 11.2a Opel Meriva vector oriented design in XGTD](image1)

![Figure 11.2b Opel Meriva CAD faces design in XGTD](image2)
The main important parts of the car (see figure 11.3a) are the outer and inner layer, the windows and the seats.

First of all, the rear-view mirrors, the wheels and many little faces are deleted because of the fact that they do not affect the indoor channel. Secondly, the XGTD software joins coplanar faces and simplifies them. The original vehicle has 31,492 faces and the simplified 4,143. Even though this is an automatic option, it takes hours. Finally, the faces are triangulated; this feature simplifies the software calculation.

Figure 11.3a Opel Meriva vector oriented design simplified

Figure 11.3b Opel Meriva CAD faces design simplified
XI.3.2 Simplified car model

To have fast simulations a simplified car is modeled. The dimensions are obtained from the official web page [7]. The chassis has 75 faces and each of the 5 seats have 12 faces.

![Figure 11.4a Opel Meriva vector oriented design simplified](image1)

![Figure 11.4b Opel Meriva CAD faces design simplified](image2)

XI.3.3 Scenarios

In order to measure the channel inside the car two scenarios will be investigated. The transmitter is an omni-directional antenna, which emits at 5GHz 0dB. It is placed on the middle of the dashboard, two omni-directional receivers are investigated, one at the right-back rear seat (NLOS) and the other at the central back seat (LOS). The NLOS antenna is more far from the transmitter than the LOS one, therefore the received power of the NLOS antenna is supposed to be lower.

Also a XY-Grid of antennas is simulated to know the power of each point inside the car.
Five scenarios are studied in the simplified car:

The first scenario is the most reflective environment, the chassis, the windows and the seats are made of a perfect electrical conductor material.

In the second scenario the chassis is medium conductor $\sigma=270$ S/m, the windows are of glass $\sigma=2.4$ S/m and the seats are low conductors $\sigma=1.2$ S/m.

The third scenario is the chassis is medium conductor $\sigma=270$ S/m, the windows are made of glass $\sigma=2.4$ S/m and the seats are absorbers.

The forth scenario, the chassis is a low conductor $\sigma=27$ S/m, the windows are made of glass $\sigma=2.4$ S/m and the seats are absorbers.

The last scenario, the chassis is a low conductor $\sigma=27$ S/m, the windows are absorbers and the seats are absorbers too.
Due to the fact that the accurate model it takes long time the simulation, only one scenario is studied. The chassis has a conductivity of 270 S/m, and the windows are made of glass, $\sigma=2.4$ S/m.

**XI.4 Discussion of results**

The results are summarized at the Annex A.

The result obtained by the accurate model and the simplified are, in general terms, the same. That shows that it is not needed a high complex model. On the other hand, the phase consideration in the simplified model could give inaccurate results as the phase depends of small details that are not simulated.

In order to describe the channel, the complex impulse response has been computed. As before, the impulse response ends very early (20ns), which is not enough to take big conclusions in a real environment.

The environment was supposed to be homogenous like a reverberation chamber, but the XY-grid of antennas shows that there is a high path loss difference between points inside the car. It is the same problem that previously, there are more than 200 paths and more than 6 reflections.

Despite this, the first paths are well simulated; the direction of arrival (DoA) and of departure (DoD) of them could be useful.

The path loss was expected to be between -40 and -44dB, except the two first scenarios, where the conductivity is very high, the other three with less reflectivity, the results agree with the empirical model. It was also found that the simulation of windows with glasses or without does not affect the received power, as the paths that arrive from reflections with the chassis are more powerful.

The Q-factor cannot be calculated by the approximation of the delay spread. The delay spread obtained is close to 1ns at all the scenarios, and it should be ten times bigger.
XII. GENERAL CONCLUSIONS

The three-dimensional simulation of a reverberation chamber was presented in this thesis. The goal was not accomplished as the software was not able to simulate this environment. Neither the early-field approximations could solve problem.

From the beginning the simulations were not accurate through lack of paths and reflections. Each model tried to solve the problems of the previous, and the result was another problem.

The XGTD software, which is good to simulate anechoic chambers, buildings and cities, is not capable to simulate a high-reflective environment like the reverberation chamber or the in-vehicle wireless channel.

To simulate this channels is needed a specific software that operate with hundreds of reflections and thousands of paths. Also, it will be good to implement a macro to move the stirrer. It was a waste of time to save the results and return to start each 30 or 40 for each stirrer position. With an automatic moving stirrer, the user could simulate the chamber without being in front of the computer.
ATTACHED DOCUMENTS
ANNEX A: Gallery of results

Figure A1, Chassis PEC, windows PEC Seats PEC, Phase consideration

Figure A2, Chassis PEC, windows PEC Seats PEC, Power addition
Figure A3, Chassis $\sigma=270$ S/m, windows Glass $\sigma=2.4$ S/m Seats PEC, Power addition

Figure A4, Chassis $\sigma=270$ S/m, windows Glass $\sigma=2.4$ S/m Seats PEC, Phase consideration
Figure A5, Chassis $\sigma=270$ S/m, windows Glass $\sigma=2.4$ S/m Seats absorber, Power addition

Figure A6, Chassis $\sigma=270$ S/m, windows Glass $\sigma=2.4$ S/m Seats absorber, Phase consideration
Figure A6, Chassis $\sigma=27$ S/m, windows absorber Seats absorber, Phase consideration

Figure A7, Chassis $\sigma=27$ S/m, windows absorber Seats absorber, Power addition
### Scenario A

<table>
<thead>
<tr>
<th>Reflections</th>
<th>Diffraction</th>
<th>Delay LOS (s)</th>
<th>Delay NLOS (s)</th>
<th>Pr LOS (dBm)</th>
<th>Pr NLOS (dBm)</th>
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Table A1, Scenario A results

### Scenario B

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<th>Delay NLOS (s)</th>
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Table A2, Scenario B results

### Scenario C

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<th>Delay NLOS (s)</th>
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Table A3, Scenario C results

### Scenario D

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<th>Reflections</th>
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<th>Delay LOS (s)</th>
<th>Delay NLOS (s)</th>
<th>Pr LOS (dBm)</th>
<th>Pr NLOS (dBm)</th>
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Table A4, Scenario D results

### Scenario E

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<th>Delay NLOS (s)</th>
<th>Pr LOS (dBm)</th>
<th>Pr NLOS (dBm)</th>
</tr>
</thead>
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Table A5, Scenario E results

### Real Scenario

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<th>Delay NLOS (s)</th>
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</table>

Table A6, Accurate Scenario results
ANNEX B, Finite Difference Time Domain Formulations

in order to solve transient electromagnetic phenomena in the time domain, we could discretize the homogeneous time domain wave equation in Cartesian coordinates,

$$\nabla^2 E_z - \frac{1}{c^2} \frac{\partial^2 E_z}{\partial t^2} = 0$$

(B.1)

by approximating both the Laplacian operator and the second time derivative by central differences. The latter term becomes

$$\frac{d^2 E_z}{dt^2} \approx k+1E_z(l, m, n) - 2kE_z(l, m, n) + k-1E_z(l-1, m, n) \over (\Delta t)^2$$

(B.2)

where the prescript k is the discrete time index, and Δt the time step (t=kΔt). We can then use the same solution strategies that we described for static and time-harmonic problems, provided that the values of Ez are specified for the first two time steps. Alternatively, the starting field values and their first time derivatives may be specified as initial conditions.

Figure B.1, Two-dimensional FDTD grid (Yee cells) for the TM-to-y case. The sampling positions for the electric and magnetic field components are staggered in space and time.
The FDTD approach is shown for the two-dimensional TM-to-y case in Figure B.1. In Cartesian coordinates the curl equations reduce in this case to the following three scalar differential equations:

\[ \frac{dE_y}{dx} = -\mu \frac{dH_z}{dt} \]  
\[ \frac{dE_y}{dz} = \mu \frac{dH_x}{dt} \]  
\[ \frac{dH_x}{dz} - \frac{dH_z}{dx} = \varepsilon \frac{dE_y}{dt} \]

To obtain central difference approximations of these expressions, the discrete simples of the electric and magnetic field components are staggered in both space and time. This means that the instances and positions of the electric field samples are defined half way between those of the magnetic field samples. If the electric field component \( E_y \) is sampled at the discrete time points \( k \) and the discrete positions \( (l, n) \), then the magnetic field components \( H_x \) and \( H_z \) are sampled at time points \( k + 1/2 \) and at positions \( (l, n + 1/2) \) and \( (l + 1/2, n) \), respectively. Hence,

\[ \frac{kE_y(l+1, n) - kE_y(l, n)}{\Delta x} = -\mu \frac{k+1/2H_z(l+1/2, n) - k-1/2H_z(l+1/2, n)}{\Delta t} \]  
\[ \frac{kE_y(l, n + 1) - kE_y(l, n)}{\Delta z} = \mu \frac{k+1/2H_x(l, n + 1/2) - k-1/2H_x(l, n + 1/2)}{\Delta t} \]  
\[ \frac{k+1/2H_x(l, n + 1/2) - k+1/2H_x(l, n - 1/2)}{\Delta z} \] 
\[ \quad + \frac{k+1/2H_z(l+1/2, n) - k+1/2H_z(l-1/2, n)}{\Delta x} \] 
\[ \quad + \frac{kE_y(l+1/2, n) - kE_y(l, n)}{\Delta t} \] 
\[ \quad = \varepsilon \frac{k+1/2E_z(l, n) - kE_y(l, n)}{\Delta t} \]
These expressions are also referred to as field update equations since they allow us to explicitly compute future values of the H-field components from their previous values and the present spatial variations of the E-field, and vice versa. Appropriate initial and boundary conditions must be defined before the update process begins. The fully three-dimensional version of the FDTD approximation of Maxwell’s curl equations involves six update equations, one for each field component.

Figure B.2 shows a unit FDTD cell (Yee cell) of a Cartesian space grid. Continuous space and time coordinates are replaced by discrete coordinates l\Delta x, m\Delta y, n\Delta z, k\Delta t, where l, m, n, k are integers and \Delta x, \Delta y, \Delta z, and \Delta t are the space and time steps. Note that the three electric field components are defined along the cell edges, while the magnetic field components are normal to the cell faces. The staggering of the field components by one-half of the cell dimensions allows for the central difference approximation of the differential operators. For the same reason, electric and magnetic field components are also staggered in time, the electric field components being defined at time points k\Delta t, and the magnetic field components at (k+1/2)\Delta t. While a cubic Yee cell yields the simplest FDTD algorithm, the three cell dimensions can, in general, be different. If we assume that \Delta x = p\Delta l, \Delta y = q\Delta l, \Delta z = r\Delta l, where \Delta l is the unit reference length, and the scaling coefficients p, q, and r are all smaller or equal to unity, then the finite difference update equations for the electric and magnetic field components in each cell are given by

\[
\begin{align*}
{k + \frac{1}{2}}E_x(l + \frac{1}{2}, m, n) &= kE_x(l + \frac{1}{2}, m, n) \\
+ \frac{s}{q}\{k + \frac{1}{2}H_x(l + \frac{1}{2}, m + \frac{1}{2}, n) - k + \frac{1}{2}H_x(l + \frac{1}{2}, m - \frac{1}{2}, n)\} \\
+ \frac{t}{r}\{k + \frac{1}{2}H_y(l + \frac{1}{2}, m, n - \frac{1}{2}) - k + \frac{1}{2}H_y(l + \frac{1}{2}, m, n + \frac{1}{2})\}
\end{align*}
\]  

(B.9)
Figure B.2 Three-dimensional Yee cell showing the staggered positions of the field component samples.

\[
k_{l+1}E_x(l, m, n+\frac{1}{2}) = kE_x(l, m, n+\frac{1}{2})
+ sy\{[k_{l+\frac{1}{2}}H_y(l, m, n+\frac{1}{2}) - k_{l+\frac{1}{2}}H_x(l, m+\frac{1}{2}, n+\frac{1}{2})]/r \}
\]

\[
k_{l+1}E_y(l, m, n+\frac{1}{2}) = kE_y(l, m, n+\frac{1}{2})
+ sz\{[k_{l+\frac{1}{2}}H_y(l, m, n+\frac{1}{2}) - k_{l+\frac{1}{2}}H_y(l, m+\frac{1}{2}, n+\frac{1}{2})]/q \}
\]

\[
k_{l+\frac{1}{2}}H_x(l, m, n+\frac{1}{2}) = k_{l+\frac{1}{2}}H_x(l, m, n+\frac{1}{2})
+ sx\{[kE_y(l, m, n+1) - kE_y(l, m+\frac{1}{2}, n)])/p \}
\]

\[
k_{l+\frac{1}{2}}H_y(l, m, n) = k_{l+\frac{1}{2}}H_y(l, m, n+\frac{1}{2})
+ sy\{[kE_x(l, m, n+1) - kE_x(l+\frac{1}{2}, m, n+1)])/r \}
\]

\[
k_{l+\frac{1}{2}}H_z(l+\frac{1}{2}, m, n) = k_{l+\frac{1}{2}}H_z(l+\frac{1}{2}, m, n+\frac{1}{2})
+ sz\{[kE_z(l+1, m, n+\frac{1}{2}) - kE_z(l, m, n+\frac{1}{2})]/p \}
\]
where

\[
\begin{align*}
& sx = Z_0 c \Delta t / (\varepsilon_{rx} \Delta l) \quad sx' = c \Delta t / (\mu_{rx} Z_0 \Delta l) \\
& sy = Z_0 c \Delta t / (\varepsilon_{ry} \Delta l) \quad sy' = c \Delta t / (\mu_{ry} Z_0 \Delta l) \\
& sz = Z_0 c \Delta t / (\varepsilon_{rz} \Delta l) \quad sz' = c \Delta t / (\mu_{rz} Z_0 \Delta l)
\end{align*}
\]  

(B.15)

In these expressions, \(c\) and \(Z_0\) are the velocity of light and the wave impedance in vacuo, and \(\varepsilon_{rx}\), \(\varepsilon_{ry}\), \(\varepsilon_{rz}\) and \(\mu_{rx}\), \(\mu_{ry}\), \(\mu_{rz}\) are the diagonal elements of the relative permittivity and permeability tensors of the medium, respectively. This algorithm explicitly updates each field component in a leapfrog time-stepping process. The future value of each E-field component is computed from its previous value and from the four H-field components circulating around it, and vice versa. The permittivity and permeability can be different in each cell, thus allowing the representation of inhomogeneous media. Losses can be included as well by carrying and discretizing the loss terms in Maxwell’s curl equations.
REFERENCES


Internation symposium on Wireless Vehicular Communications (WIVEC’07), Baltimore (USA), Sept. 2007


[7] Opel Meriva dimensions (spanish):
ebSiteId=GBPES#1


COMPLEMENTARY REFERENCES


[UMT] UMTS 30.03, “Universal Mobile Telecommunication System (UMTS); Selection procedures for the choice of radio transmission technologies of the UMTS”